Technical University of Denmark

MR principles, imaging and contrast
Diagnostic imaging techniques Ph.D. course

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Diagnostic imaging techniques Ph.D. course

- Software and animations: http://www.drcmr.dk/bloch and http://www.drcmr.dk/MR

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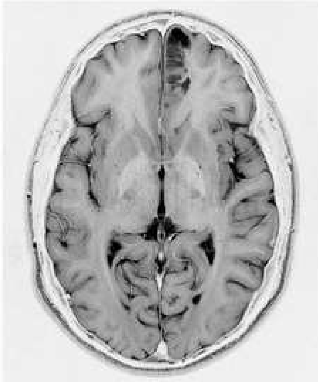


An axial MRI of an almost normal brain.

Based on radiowaves coming from the body.

Todays lecture: Learn how and what the image tells us about the tissue.

Overview

Basic NMR
- Nuclear spin and magnetization
- Precession
- Resonance and excitation
- Pulse sequences

Contrast
- Relaxation

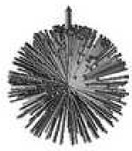
Imaging
- Slice selection
- Phase rolls
- k-space

Motivation:
- MRI understanding is needed for interpretation, e.g. of contrasts.

Supplementary material

Lecture notes:
- http://www.drcmr.dk/
- 47 pages in English or Danish

Animations and software:
- http://www.drcmr.dk/MR
- http://www.drcmr.dk/bloch



Magnetic Resonance basics

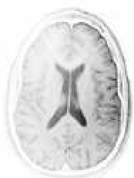
Equipment

You need...

magnet

radio wave emitter and receiver (coils)

- Transmitter coil:
  - Typically built into the scanner (body coil)
- The receiver coil:
  - Preferably close to the region of interest
  - Often consists of a number of smaller coil elements.
  - No moving parts

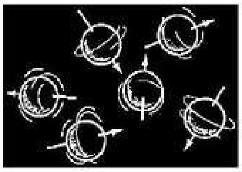


Nuclear spin

Certain nuclei possess "spin"

- H-1, P-31, C-13, F-19, Na-23, He-3,...

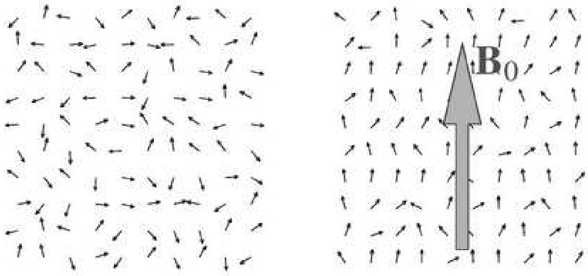
Protons (Hydrogen nuclei):



Proton spin gives rise to magnetic property:
Hydrogen nuclei behave like bar magnets with angular momentum

Influence of the magnetic field

Partial alignment of the magnetic moments:

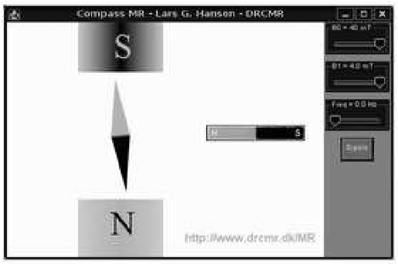


A macroscopic magnetization is formed.
The equilibrium magnetization is along the magnetic field.
Why not full alignment?

- Molecular tumbling, thermal motion and nuclear interactions.

Magnetic Resonance

Java applet at http://www.drcmr.dk/MR:



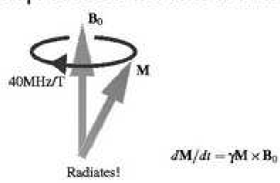
Precession

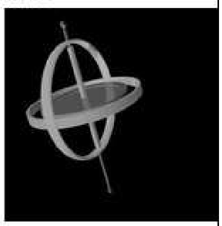
When a compass needle is flicked...

- ...it oscillates in a plane through north.

When a proton is flicked...

- ...the magnetization precesses in a cone around north:



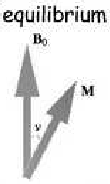


The difference is due to rotation of the protons.

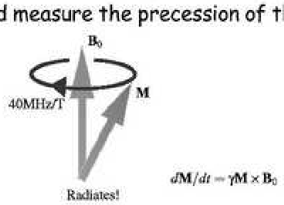
The MR signal

The basic MR experiment:

- Place patient in the strong magnetic field.
- Apply radio waves pushing the equilibrium magnetization.
  - E.g. a 30 degree rotation.



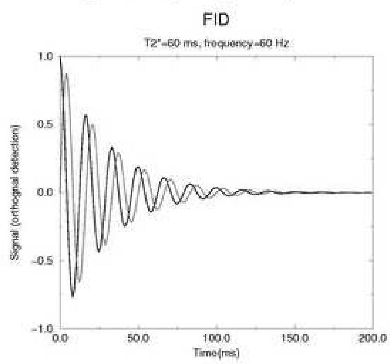
- Switch off RF and measure the precession of the magnetic dipole:



- Analyze the weak emitted radio signal.

The MR signal(2)

MR signal with a single frequency component:

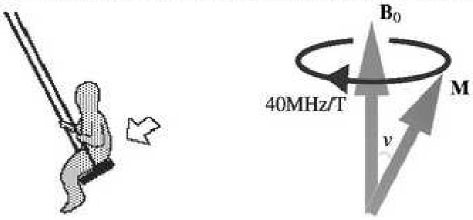


Orthogonal coils detect changes in Mx, My, respectively.
The signal intensity is reflected in MR images.

Excitation

Resonance:

The perturbation is induced by radio waves (excitation).
Large effect if the system is pushed at the right frequency.

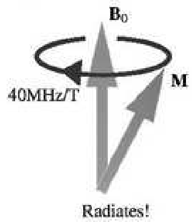


Pushing the swing at the eigen-frequency changes the amplitude.

Radio waves at the Larmor frequency changes the angle v.

Precession

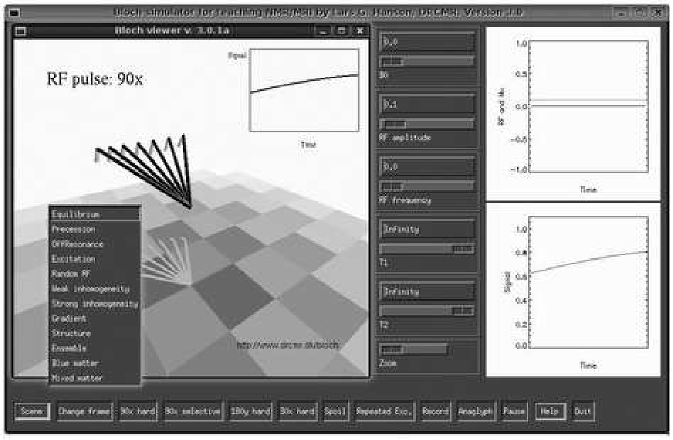
Reestablishing the equilibrium after excitation:



$d\mathbf{M}/dt = \gamma\mathbf{M} \times \mathbf{B}_0 + \text{relax. terms}$

The system returns to thermal equilibrium.
Radio waves are emitted and detected.
The magnetization recovers and the signal decays away.

Animated Bloch Dynamics



▸ Runs directly in browser from http://www.drcmr.dk/bloch. Also at YouTube.

Animated Bloch Dynamics

$$d\mathbf{M}/dt = \gamma\mathbf{M} \times (\mathbf{B}_0 + \mathbf{B}_1(t)) + \text{relaxation terms}$$

Precession
Resonant excitation (soft pulses)
Non-selective excitation (hard pulses)
Transversal and longitudinal relaxation
The spin ensemble
The rotating frame of reference

starring

B_0 : The main magnetic field along z
$\omega_0 = \gamma B_0$: The Larmor precession frequency
ω : The RF field frequency
B_1 : The amplitude of the transversal RF field (i.e. in the xy-plane)
T_2 : The transversal relaxation time (i.e. orthogonal to B_0)
T_1 : The longitudinal relaxation time (i.e. along B_0)

Contrast

Image contrast

Many influences on the signal:

- Water content (proton density, PD).
- Relaxation (local nuclear environment).
- Flow, perfusion and diffusion.
- Neuronal activation.
- Metabolic properties.
- ...

Unwanted contrast:

- Coil sensitivity variation.
- Field inhomogeneity.
- Motion artifacts.

Relaxation time contrast

Typical radiologist statement after MRI exam:

"PD- and T1-weighted imaging were normal.
T2-weighted imaging revealed a subcortical lesion".

T1, T2 and proton density (PD) are parameters characterizing tissue:
- just like "temperature" or "water content".
- The "proton density" is, in fact, the water content.

T1 and T2 time-constants are somewhat special:
- Can only be determined by MRI (they are "MR contrast parameters")
- Reflect aspects of consistency (molecular mobility)

So what is "weighting" ??
- The parameters above are seldom measured quantitatively...
- ...but their relative values may be apparent in the images.
- i.e: The contrast in a "T1-weighted" image comes mostly from T1-differences.

So why all this talk about T1 and T2?

Relaxation time contrast

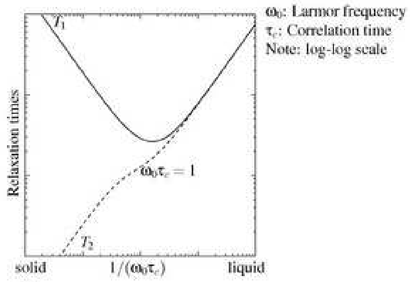
T1- and T2-weighted imaging
- The work horses of clinical imaging:
  - Always available, reliable and require little post-processing

T1- and T2-weighted sequences.

- Transversal T2-relaxation
  - Loss of signal due to dephasing of spins
  - Irreversible loss caused by nuclear interactions
  - Reversible loss caused by inhomogeneity (shortens T2 into T2*)
- Longitudinal T1-relaxation
  - Return of Mz to equilibrium
  - caused by inelastic nuclear interactions only (so T2<T1)

Relaxation for simple substances

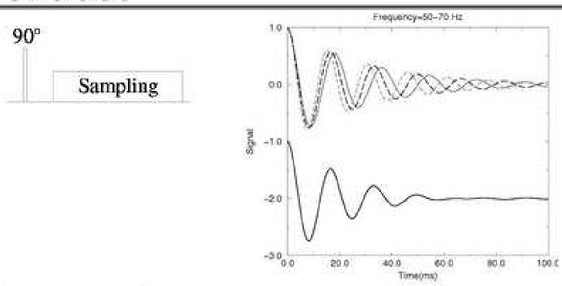
Relaxation time dependence on motional frequency:



- Solids: Short T2, Long T1
- Liquids: Long T2=T1.
- Intermediate: Intermediate

The Larmor frequency depends on the field strength
- High field shifts properties toward solid regime.

T2* contrast



Signal decay time T2* < T2.

Field inhomogeneity result from...
- limited hardware capabilities.
- variations in magnetic properties of tissue/air/bone.
- variations in magnetic properties on a microscopic scale.
  - e.g. around capillaries

T2* contrast

Signal drop-out due to inhomogeneity
- here caused by dental fillings.

T2* contrast can be useful, e.g., for
- studies of neuronal activation.
- perfusion studies.
- detection of hemorrhage (bleeding).

The signal is recovered by...
- shortening the time from excitation to readout (the echo time, TE),
- using a spin-echo sequence

Start simulator

Contrast agents

Contrast agents:
Normally a paramagnetic substance (e.g. Gadolinium complex)
Used commonly to change relaxation rates

Before and after administration of contrast:
Only acute MS lesions are hyper intense (BBB opened in acute phase)

Important: The effect of CA on water is seen, not the CA itself!

Contrast agents

Fast brain imaging during contrast injection (bolus):

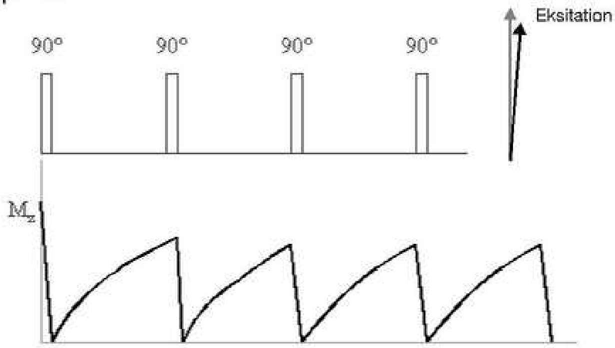
One second interval between images.

- The contrast agent is Gd-DTPA, but deoxy-Hb has a similar effect.
  - Useful for functional mapping.

T1 contrast, saturation

Partial recovery of the longitudinal magnetization:

- Repetition time TR ~ T1



Conventional contrast

PD-weighting (proton density, water content):

- Long repetition time: TR >> T1
  - Full T1 relaxation.
- Short echo time: TE << T2
  - No T2 signal decay.

T2-weighting:

- Long repetition time: TR >> T1
  - Full T1 relaxation.
- Long echo time: TE ~ T2
  - Significant T2 signal decay.

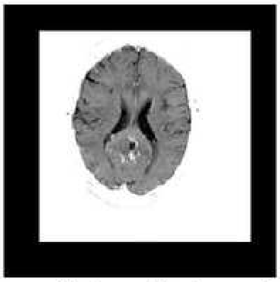
T1-weighting:

- Short repetition time, TR ~ T1
  - No time for relaxation (saturated measurement).
- Short echo time, TE << T2
  - No T2 signal decay.

More contrast mechanisms

Contrast agents revisited

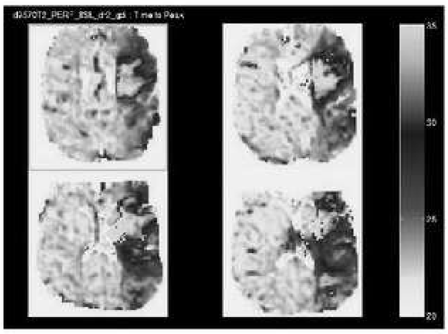
Fast imaging after contrast injection (bolus):



One second interval between images.

CA-based perfusion measurements

Measurement of blood supply:

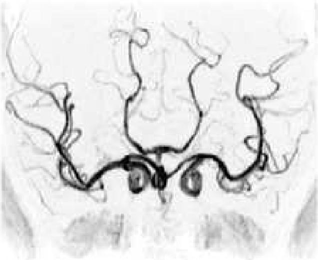


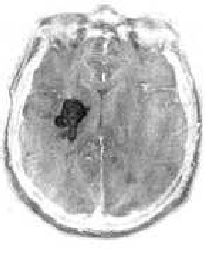
Duration before bolus arrives in tissue

- Quantitating the perfusion requires deconvolution or spin labelling.

Flow and diffusion weighting

Flow and diffusion weighting.

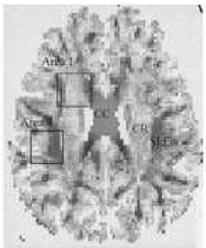


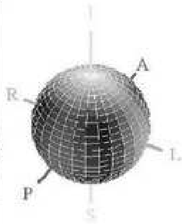


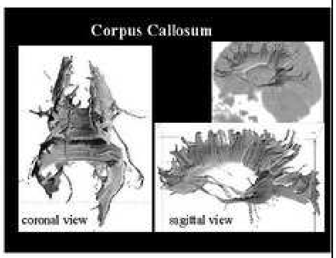
Fiber directionality

Measuring nerve-fiber directionality

- The diffusion is high along the nerve fibers.
- The "diffusion tensor" describes anisotropic diffusion
  - a generalization of diffusion coefficient (matrix)
- Measured by repeated diffusion weighting in various directions
- Basis for tractography



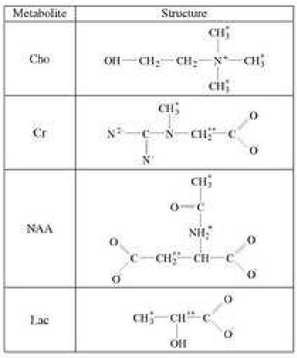




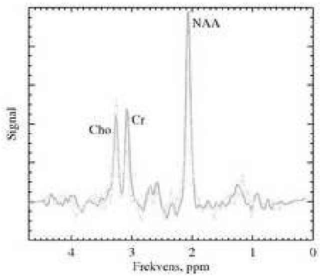
Spectroscopy

MR can distinguish chemical substances

- Molecular structure influences local magnetic field



Sclerosis and spectroscopy



Marked regions:

- Normally appearing white matter(solid curve).
- Lesions(dashed curve).

Increased choline reflects turn-over of cell membranes.
Possibility of characterising normally appearing white matter.

Functional imaging, fMRI

Activation of brain:

- Increased oxygen consumption
- Increased blood supply.
- Increased oxygen conc.
- Changed relaxation times.
  - deoxy-haemoglobin is paramagnetic.
- Changed MR signal.
  - Activation: Signal increases.
  - Rest: Signal decreases.

Examples:
visual stimulation
language lateralisation.

Language lateralisation, fMRI

Difficult task with pitfalls:

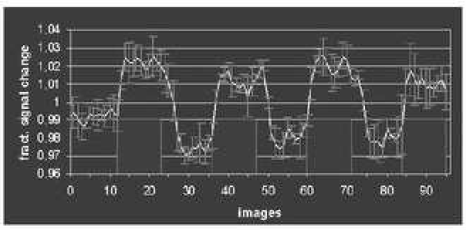
- Localization of language areas ahead of surgery.

Semantic task:

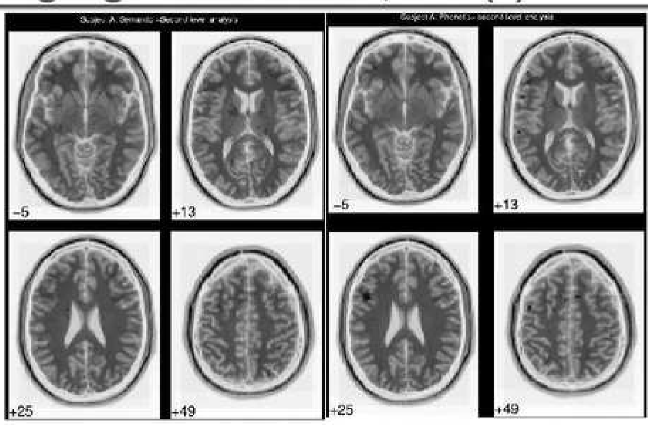
- Patient switch between word generation and rest.
  - Categories "fruit", "month", "animal", "tree",...

Phonetic task:

- Patient switch between word generation and rest.
  - Initial letter "F", "R", "E", "T",...



Language lateralisation, fMRI(2)



Regions activated by semantic and phonetic tasks.

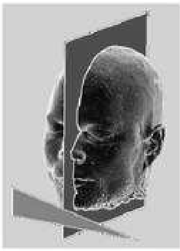
Imaging

Gradients

Slice selection:

Apply gradient from left to right.
All spins within the plane oscillate at the same frequency.

Only spins on resonance are affected by RF.



Two dimensions left to resolve...

Spatial encoding, 1D

Spin orientation immediately after excitation:

"Phase roll" after application of a gradient:

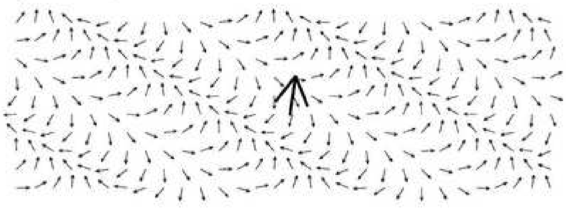
- No net magnetization (no signal).

If e.g. bone replaces some of the hydrogen nuclei above:

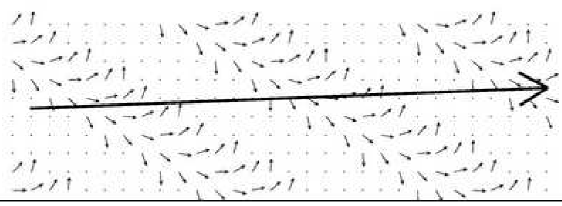
- Net magnetization and signal if the structure matches phase roll.

Spatial encoding, 2D

Hardly any net magnetization:

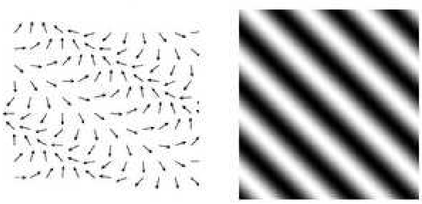


Large net magnetization and signal:



Imaging

Alternative visualization of phase roll (wave) patterns:



Lesson so far:

If the object has periodic variation in the water content,...

- ...then application of a matching gradient will give significant signal.

Turning it around...

By application of gradients, we can measure how "striped" the patient is.

- This is imaging in a nut shell!

Imaging in a nut shell

Measurement:

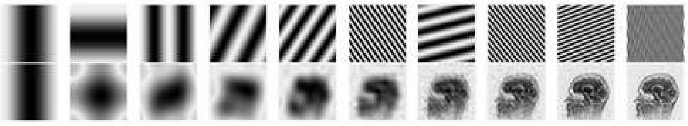
We measure how "striped" the patient is for all stripe patterns.

- The patterns are "drawn" in the patient one by one.
- The MR signal strength reflects the stripedness.

Image reconstruction:

We add all possible stripe patterns together (weighted sum).

- The amount of each pattern is the signal strength measured above.
- Like stacking overheads...

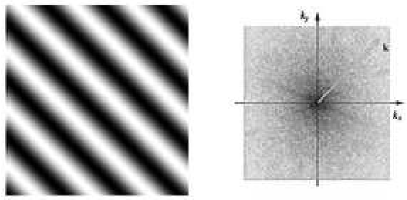


- Bottom row is sum of patterns. Upper row is last pattern added.
- The number of patterns is doubled in each step.

Keeping track of patterns: k-space

To each wave pattern...

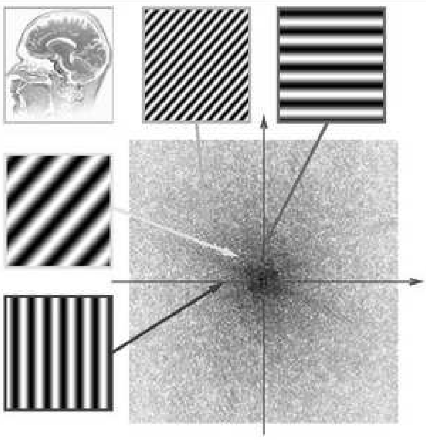
- is assigned a wave vector "k" which is
  - pointing towards the direction of variation.
  - having a length being the frequency of the variation.



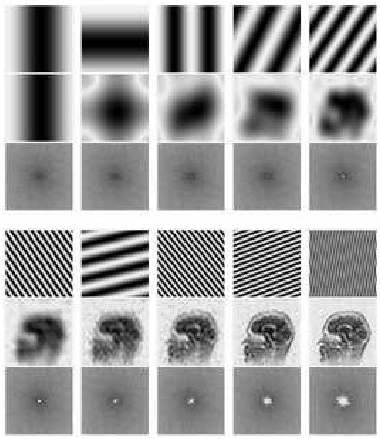
The similarity of the object to each wave pattern can be measured:

- Apply gradient to induce spatial phase roll pattern.
- The signal reflects the similarity of the object and the pattern.
- The signal is recorded in k-space,
  - i.e. as a function of pattern or, equivalently, k.

The structure of k-space



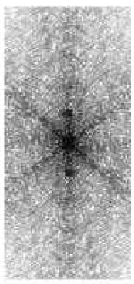
Reconstruction



- BTW: This is the Fourier transform -- a weighted som of phase rolls.

Find Waldo in k-space

"Find Holger i k-rummet":



Find Waldo in k-space

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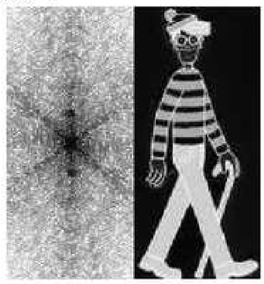

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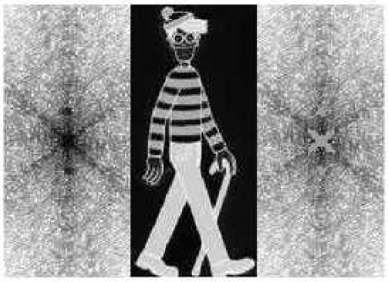
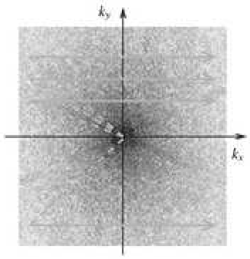


Traversing k-space

Spin warp imaging:



Moving in k-space:

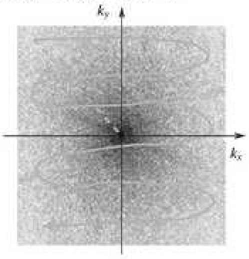
$$\mathbf{k}(t) = \gamma \int_0^t \mathbf{G}(t')\,dt'$$

So velocity in k-space equals gradient:

$$d\mathbf{k}(t)/dt = \gamma \mathbf{G}$$

Alternative sequences

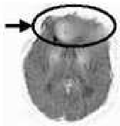
Why line-by-line? Why not single-shot?



Echo planar imaging (dogma EPI). TA ~ 100 ms.

High temporal resolution, but no magic:

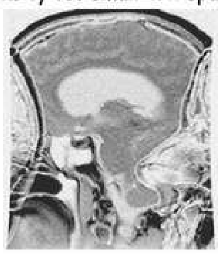
- Short duration is reflected in SNR.
- Demanding for hardware.
- Prone to artifacts.



Artifacts

Most artifacts are best understood in k-space:

- Aliasing: Sampling density too small in k-space:



- Ghosting: Left/right asymmetry in k-space sampling.
  - Shadow displaced by FOV/2.
- Motion during k-space traversal.
  - e.g., periodic flow giving displaced copies of arteries.

Surface scratching

There is much more to it. Sources of contrast:

- Relaxation
- Flow, perfusion and diffusion.
- Exchange
- Neuronal activation.
- Metabolic properties.

- Chemical exchange
- Metabolic conversion
- pH, intra- and extracellular
- Temperature
- Mechanical properties
- Electrical properties
- Magnetic properties
- ...

Supplementary material

Lecture notes:

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